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Optical Emission from High Velocity Clouds and the Ionization Sources in the Galactic Halo

Benjamin J. Weiner

UCO/Lick Observatory, University of California, Santa Cruz, Santa Cruz, CA 96064

Stuart N. Vogel

Department of Astronomy, University of Maryland, College Park, MD 20742

T.B. Williams

Department of Physics & Astronomy, Rutgers University, 136 Frelinghuysen Rd., Piscataway, NJ 08854

Abstract. Optical emission lines have now been detected from about 20 high velocity clouds. These emission lines – primarily Hα, secondarily [N II] and [S II] – are very faint and diffuse, spread over the surfaces of the clouds. We compile emission line measurements and present a model in which the Hα is recombination caused by photoionizing radiation escaping the Milky Way. In such a model, we infer HVC distances of 5–30 kpc. The photoionization model fails to explain the relatively strong Hα emission from the Magellanic Stream, and the O VI absorption seen by FUSE in HVCs and the MS, which require a second source of ionization (likely collisional). Regardless of mechanism, the fact that HVCs are detectable in Hα indicates they are not far away enough to be Local Group objects. Adopting the HVC distances from the model, there appear to be two classes of HVCs: Hα-bright clouds with low velocity deviations from Galactic rotation, and often strong [N II], which are presumably affiliated with the Galactic disk; and Hα-faint clouds with high velocity deviations, which are likely to be infalling gas.

1. Introduction

High velocity clouds (HVCs) are clouds of neutral hydrogen which generally appear distinct from the Galactic H I disk. Cataloged HVCs generally have relatively low H I column densities, $10^{18} - 10^{20.5}$ cm^{-2}, and are large, from 0.5 degrees to tens of degrees across; see the review of Wakker & van Woerden (1997). No optical counterparts such as stars are known in HVCs, and the only distance constraints are for a few HVCs complexes that are seen in absorption against background halo stars, at several kpc. Thus HVC distances, sizes, and masses are quite uncertain, allowing a wide range of models for their origin.

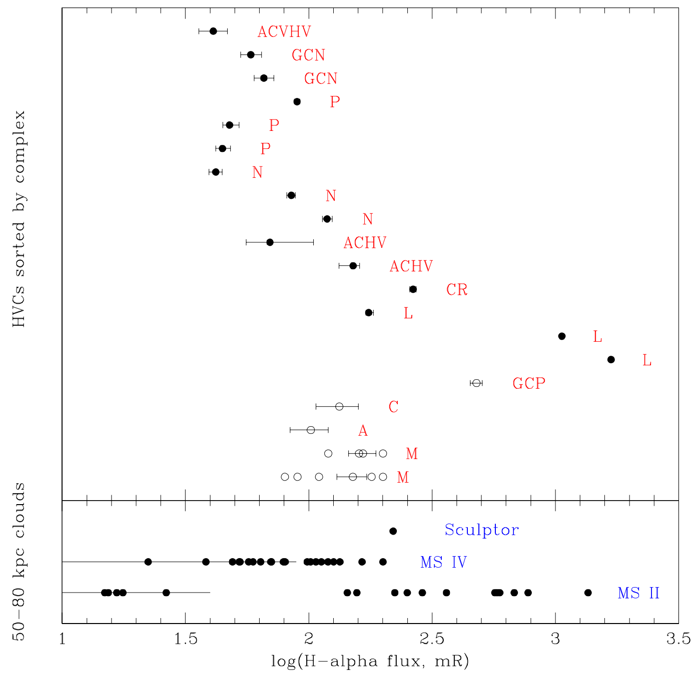

Figure 1. Hα emission from HVCs (upper panel), and the Magellanic Stream and Sculptor DSph (lower panel). The HVCs are grouped by complex (ACVHV, GCN, etc.; Wakker & van Woerden 1991) along the y-axis, each line being one HVC. Open circles: M, A, and C from Tufte *et al.* (1998), and GCP from Bland-Hawthorn *et al.* (1998). Filled circles: our data from LCO and CTIO.

Popular models of HVCs include: recycling of disk gas through a Galactic fountain (*e.g.* Bregman 1980); stripping from Galactic satellites; and infall of possibly primordial gas, such as Local Group models (Giovanelli 1981; Blitz *et al.* 1999). These models place HVCs at from < 10 kpc to ~ 1 Mpc respectively, a range of 100 in distance and 10^4 in gas mass. The Blitz *et al.* revival of the Local Group model, incorporating dark matter, has attracted recent attention and controversy: it puts the HVCs at large distances, increasing their masses, and is potentially related to CDM small halo overpopulation issues (Klypin et al. 1999; see Gibson et al. , these proceedings).

A wide variety of tests of HVC intragroup models have been proposed (see Blitz and Gibson et al. , these proceedings). Observations of Mg II absorbers and H I surveys of groups have limited the allowed H I mass in typical groups (Charlton et al. 2000, Zwaan 2001). However, we still need to understand just what our HVCs are, even if they are not Local Group objects.

Optical emission lines can provide information about individual HVCs. Faint, diffuse optical recombination lines have been seen from several HVCs (Tufte et al. 1998; Bland-Hawthorn et al. 1998; Weiner et al. 2000). The causes of this emission are not well understood. It is too faint and diffuse to be ionization from embedded stars, and is probably photoionization, by e.g. the Milky Way; or heating from external sources, such as collisions with gas in the Galactic halo. H I HVCs are optically thick to ionizing radiation, so either photoioniza-

tion or heating could raise an ionized skin on the clouds. Plausible ionization or heating sources should decline away from the Galaxy, and optical Hα emission can be an indirect indicator of HVC distance. Here we describe a sample of HVCs observed in Hα emission and explore the consequences of a simple ionization and distance model.

2. Observations

The only optical emissions detected from HVCs are spatially diffuse emission lines of Hα, [N II], and [S II]. Several groups have used Fabry-Perot spectroscopy to detect these emission lines (Weiner & Williams 1996; Tufte et al. 1998, 2001; Bland-Hawthorn et al. 1998). These emission lines are much fainter than the sky, and "chopping" between object and blank sky fields is required to achieve sky subtraction to fractions of a percent (for example spectra see Figure 1 of Weiner et al. 2000).

Hα emission of from 40 to > 1000 milli-Rayleighs (mR) has been observed from individual HVCs (1 Rayleigh $= 10^6$ photons cm^{-2} s^{-1} into 4π). Figure 1 summarizes the results obtained by several groups and indicates the HVC complexes to which the clouds belong (Wakker & van Woerden 1991). Clouds M, A, and C were observed by the WHaM group (Tufte et al. 1998), GCP by Bland-Hawthorn et al. (1998), and the remainder are our observations, mostly from Las Campanas using the Dupont 2.5-m and Wide Field Camera, built by Ray Weymann and collaborators.

A wide range of Hα flux is observed – 1.6 dex among the various HVCs. Grossly, clouds in the same complex have similar Hα flux. In a few cases such as the large northern HVCs M and A, and the intermediate velocity complex K, there are measurements from more than one place on the cloud (Tufte et al. 1998; Haffner et al. 2001) and the Hα emission varies by no more than a factor of 2–5. In contrast, the emission from the Magellanic Stream is quite spatially varied, by a factor of 30–40. Hα emission measure is not correlated with H I column density in the HVC/IVCs (Haffner et al. 2001) or the MS.

A few clouds have multiple emission lines measured. A few of the HVCs brightest in Hα, such as 343+32–140, have [N II]/H$\alpha > 1$ (see Figure 1 of Weiner et al. 2000). Similarly high [N II]/Hα ratios are observed in the extraplanar gas above NGC 891 (Rand 1998). Some of the fainter HVCs have little or no [N II], possibly indicating lower metallicity or different ionization state. In the Magellanic Stream, [N II] is detectable but [N II]/H$\alpha \sim 0.2$, a larger decrement than one might expect just from the metallicity. This decrement, combined with the large spatial variations in Hα, suggests that the MS Hα may have a different cause than the Hα-bright HVCs.

3. A model of the Galactic ionizing flux

As a first step to explain the HVC Hα emission, we consider a simple model: some amount of Lyman continuum radiation from hot stars escapes the disk of the Galaxy and ionizes the skin of HVCs. Since H I HVCs are optically thick to LyC radiation, the recombination Hα emission is proportional to the incident LyC: 0.46 Hα photons per Lyc photon at 10^4 K.

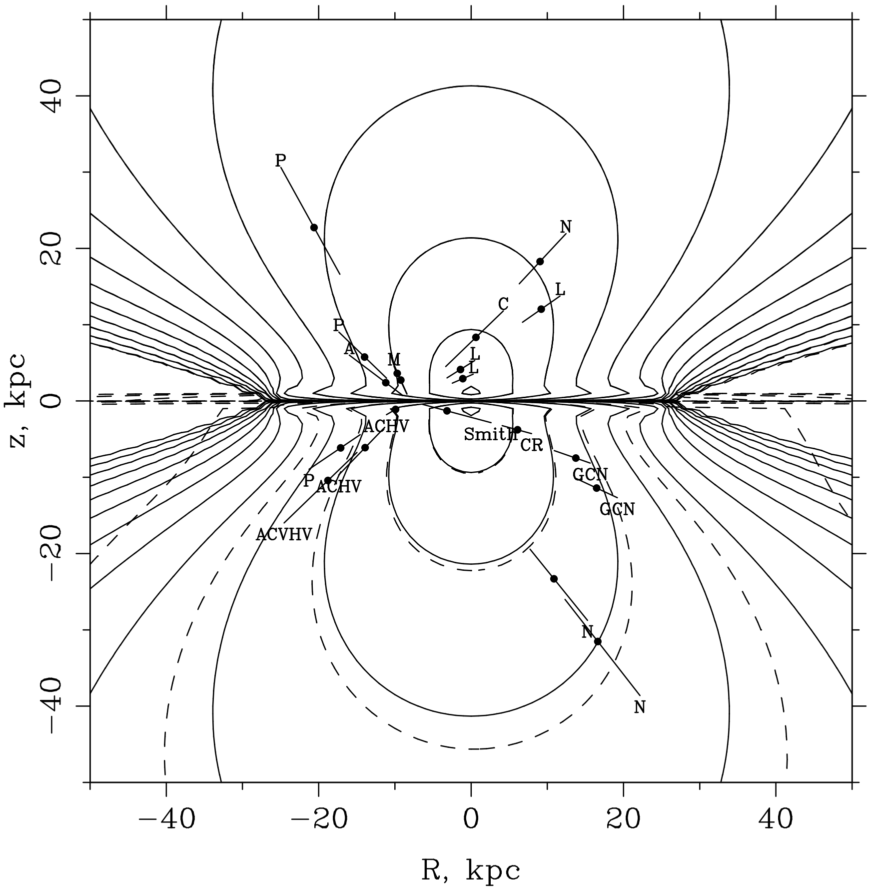

Figure 2. A simple model of the ionizing flux emergent from the Galaxy, with contours of F_{LC} from 1 to $10^{6.5}$ photons cm^{-2} s^{-1} by 0.5 dex (dashed contours include the LMC). Positions of HVCs from the simple photoionization model are indicated (rotated onto the $\ell = 180° - 0°$ plane, so that R is represented accurately).

Figure 2 shows the contours of LyC flux in this model, using an exponential disk of O stars with total LyC luminosity 2.7×10^{53} photons s^{-1}. We model the Galactic absorbing layer and Reynolds layer as a slab with one-sided face-on optical depth to ionizing photons of $\tau = 2.5$. The LyC escape fraction, when averaged over angle, is 2%. (See also the model of Bland-Hawthorn & Maloney 1999, and Weiner et al. 2000.) The small escape fraction implies that galaxies like the Milky Way do not contribute much to the extragalactic ionizing background.

We arrived at this model by using the (roughly) known total LyC luminosity, and tuning τ to achieve agreement between the known distances and Hα fluxes of HVCs A and M (Danly et al. 1993; Tufte et al. 1998; van Woerden et al. 1999). Once we know the distribution of Lyc flux in the halo, the Hα fluxes measured for other HVCs yield their distances, plotted in Figure 2. The distance "error bars" in Figure 2 assume a $\pm 50\%$ range in predicted Hα due to factors such as cloud geometry; the observational errors are much smaller. Variations on the theme of this model produce similar results.

Figure 3 plots the Hα flux of the 20 HVCs versus their Galactocentric distances as inferred from the model (or as measured for A and M). There is a strong correlation, as may be expected; the best-fit relation is $F(\mathrm{H}\alpha) \propto D^{-2.2}$, and a -2 index is a decent fit. We suggest that there's nothing particularly special about this model. Any model (photoionization or not) which has a reasonable flux-distance power law index *and* is normalized to the HVCs A and M with known distances should yield similar predictions for HVC distances.[1]

4. The need for another source of ionization

Unfortunately, photoionization models break down when we look at the Magellanic Stream, and another source of ionization is required. The MS II cloud is likely at $D \sim 50$ kpc, and shows $F(\mathrm{H}\alpha)$ from < 40 to 1300 mR. From Figure 2, the model LyC flux at MS II (40–50 kpc at $b \sim -90°$) is $\sim 10^5$ photons cm^{-2} s^{-1}, predicting $F(\mathrm{H}\alpha) \sim 45$ mR, 30 times lower than the brightest emission and 10 times below the "typical" Hα-bright spots.

There are two problems: the Hα-bright spots are too bright to be powered by flux escaping from the Milky Way, and the spatial variation is much larger than expected from a photoionized cloud skin. These problems also exist for MS IV, and have been known for some time (Weiner & Williams 1996). The deficit is much too large to make up by e.g. limb brightening. Since the model's face-on LyC escape fraction is $e^{-\tau} = 0.08$, we can't turn it up enough to explain the MS – most LyC needs to be absorbed in the Galaxy to power recombination regions. Furthermore, photoionization should produce a nearly uniform Hα flux on an H I cloud optically thick to LyC, yet the MS II emission varies spatially.

Independent evidence for another cause of ionization comes from FUSE detections of O VI absorption in the MS and in HVCs (Sembach et al. 2000, and these proceedings). With an ionization potential of 114 eV, the O VI in these clouds cannot be produced by photoionization, from Milky Way stars or

[1] More complex models, e.g. distributing the O stars in spiral arms rather than a smooth disk (Bland-Hawthorn, these proceedings), can make a difference in the detailed locations, but for HVCs several kpc above the disk, some of the complexity is integrated out.

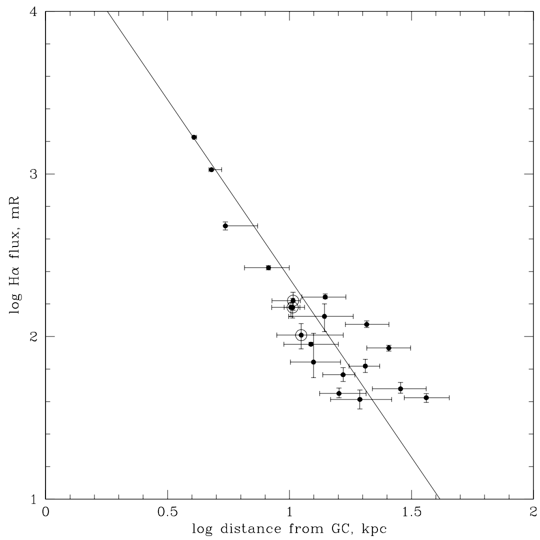

Figure 3. For the 20 HVCs from Figure 1, log Hα flux versus distance from the Galactic center, as given by the photoionization model of Figure 2. The circled points are the HVC complexes A and M used to normalize the model. The best-fit line has a slope of –2.2.

otherwise. Collisional ionization is likely required; a possible source of heating is interaction between the H I cloud and hot gas in the halo. A similar problem is seen in the extraplanar diffuse ionized gas of NGC 891 and of the Milky Way, where the line ratios require something in addition to photoionization (Rand 1998; Reynolds et al. 1999).

These anomalies point to collisional ionization of clouds in the Galactic halo, presumably through some kind of mechanical energy input such as ram pressure or turbulent mixing, as we previously argued for the Magellanic Stream (Weiner & Williams 1996). But it's difficult to see how our 1996 toy ram-pressure model could produce the peak Hα of 1300 mR now observed in MS II, at least not from collisions with halo gas of $n \sim 10^{-4}$ cm^{-3}. Perhaps the Stream is colliding with itself at MS II. The physics of Hα production from processes like ram pressure and turbulent mixing is not yet well enough understood to make detailed models. We need better theories here.

5. Distances and deviation velocities

Despite the uncertainty in the sources of ionization, it is useful to consider the implications of the HVC fluxes and distances from the simple model. There are some reasons to believe that, for example, photoionization is operating on HVCs A and M based on the modest range of Hα flux (Tufte et al. 1998). And even if there is some other ionization mechanism, it ought to depend on distance from the Milky Way; as we argued above, models with a fairly generic flux-distance power law will produce similar distances when normalized to HVCs A and M.

We can use the distance ranges to measure deviation velocities for the HVC sample. The deviation velocity is the difference between the HVC velocity and that expected for gas in Galactic rotation at the same location (Wakker & van

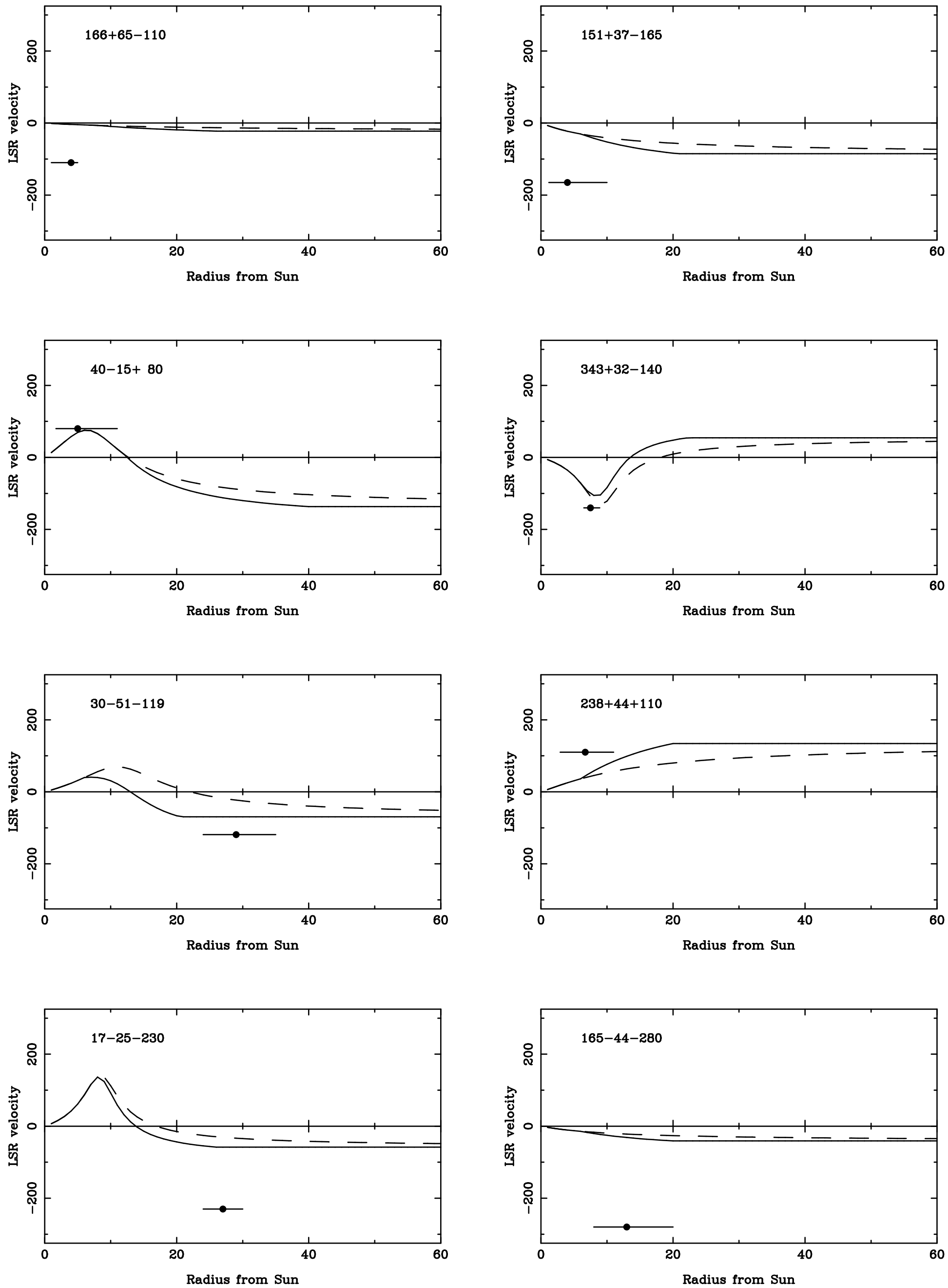

Figure 4. For 8 clouds, HVC LSR velocity and the LSR velocity expected from Galactic co-rotation are plotted as a function of distance from the Sun (dashed line: cylindrical Galactic rotation; solid line: rotation decaying with z height). The HVC distance ranges (points and error bars) are from the photoionization model of Section 3. Panels a,b: large complexes M and A. Panels c,d: Hα-bright HVCs consistent with Galactic rotation. Panels e,f: HVCs with moderate Hα and modest deviation velocity. Panels g,h: Hα-faint HVCs with large negative deviation velocity.

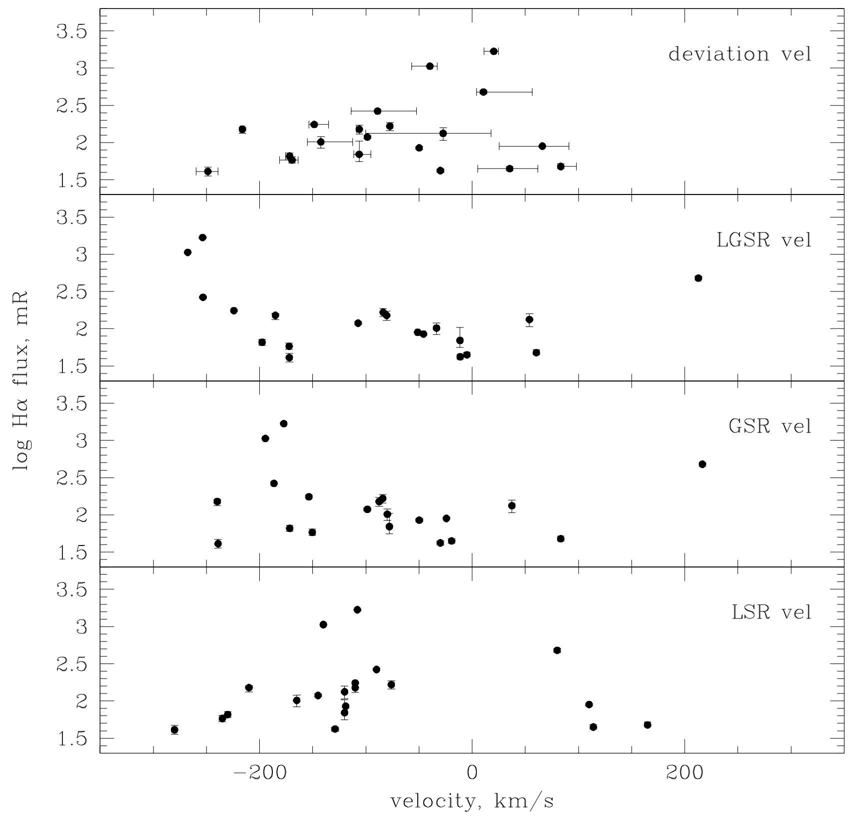

Figure 5. For the 20 HVCs from Figure 1, log Hα flux versus various measures of cloud velocity, from top: deviation velocity, Local Group (LGSR) frame, Galactic (GSR) frame, and LSR frame. By definition, HVCs must have $|V_{LSR}| > 90$ km s^{-1}.

Woerden 1991). It may be more physically meaningful than the velocity relative to the LSR, but requires knowing the HVC distance.

There is some controversy over the most appropriate measure of HVC velocity. Blitz et al. (1999) showed that the velocity dispersion of the HVC ensemble is lower in the Galactic standard of rest (GSR) than in the LSR, and lower yet in the Local Group standard of rest (LGSR), arguing that HVCs are Local Group objects. However, Gibson et al. (these proceedings) point out that the GSR, LGSR, or any measure of velocity which takes out the sinusoid caused by the LSR motion around the Galactic center will improve the HVC velocity distribution.

Figure 4 shows velocity-distance plots for 8 of the HVCs in our sample. The HVC velocity and distance range are shown together with the expected velocity for co-rotating gas. Panels (a,b) show the large, nearby complexes M and A; since these are toward the Anticenter, the co-rotating gas has little radial velocity and the deviation velocities are fairly large and negative. Panels (c,d) show 40–15+80 and 343+32–140. These clouds are Hα-bright, and their Hα fluxes place them in the inner Galaxy. At these distances, they can have deviation velocities of only a few tens of km s^{-1}; they could be disk gas recycled through a Galactic fountain. These clouds also have high [N II]/Hα. Panels (e,f)

show clouds which are moderate in Hα and deviation velocity. Panels (g,h) show 17–25–230 and 165–44–280, very high-velocity clouds (VHVCs). These clouds are faint in Hα, putting them at tens of kpc distances, and have large deviation velocities (~ -200 km s^{-1}), suggesting infall: their kinetic energy is too large to have originated in the disk.

In Figure 5, we show the relation between HVC Hα flux and measures of velocity for the 20 clouds with fluxes. These flux-velocity distributions have not been previously accessible since there were few Hα fluxes or distance estimates. The sample is not statistically complete and has some minor selection effects (e.g. the clouds observed from LCO all have $\delta < +10°$). However, we don't expect these to affect the conclusions.

The distribution of flux with LSR velocity (bottom panel of Figure 5) suggests that brighter clouds are lower velocity, but LSR velocity is less than ideal, since the LSR itself is moving (and there is an artificial void of clouds at $|V_{LSR} < 90|$). Converting to GSR velocity makes the distribution somewhat less understandable. The bright clouds actually move to higher velocities. In the LGSR frame, the same problem occurs to an even greater degree; the brightest clouds actually have the highest $|V_{LGSR}|$. (We assumed an LSR motion of 220 km s^{-1} toward $(\ell, b) = (90, 0)$ in the GSR, and of 280 km s^{-1} toward (102,-5) in the LGSR, Einasto & Lynden-Bell 1982.) If the advantage of the LGSR frame is that it minimizes the velocity dispersion of HVCs, the highest $|V_{LGSR}|$ are outliers and it is odd to find the brightest clouds among them, especially since the brightest clouds also are likely to be the closest to the Galaxy.

Using the deviation velocities we found from our HVC distance model, the flux–velocity distribution suddenly makes sense (top panel of Figure 5). The flux–deviation velocity distribution is compact (low dispersion in V_{dev}), peaks near zero V_{dev}, and has a tail to negative velocities, $V_{dev} \sim -200$ km s^{-1}. The brightest clouds (such as Figure 4c,4d) have small deviation velocities – but because they are co-rotating in the inner Galaxy, their GSR velocities are high. The tail of Hα-faint clouds at large negative V_{dev}, the VHVCs, are difficult to explain with Galactic disk-based models and are probably infalling (as was already suggested by Giovanelli 1981; Wakker & van Woerden 1991).

6. Conclusions

High velocity clouds are routinely (if not easily) detected in Hα. There are 5 detections in the literature, and our survey has 15 clouds with good spectra, and has detected Hα from each; a few other clouds have low-quality spectra and we can't set any useful limits on the Hα flux. Our faintest HVC is at 41 mR, while our 2 sigma limit is typically 11 mR, implying that the sample is not limited by flux. Recent results from the WHaM team detect 5 of 6 clouds to equally faint limits (Tufte 2001).

The lack of HVCs ultra-faint in Hα implies that HVCs are not ultra-far, for any reasonable ionization mechanism. In a simple photoionization model normalized to put the HVCs A and M at the proper distances, the HVCs in our survey are at 5–30 kpc distances. One can argue that another ionization mechanism is operating, as seems to be the case in the Magellanic Stream. But even if we scale the HVCs to the atypical brightest points on the MS, the HVCs

are within ~ 200 kpc (and then HVCs A and M are difficult to explain since they are close).

Adopting the more moderate HVC distances from the simple photoionization model of Section 3, we can find the amount by which the clouds deviate from Galactic rotation. The distribution of Hα flux with deviation velocity is very sensible looking, more so than the distribution over V_{GSR} or V_{LGSR}. The clouds brightest in Hα are at low deviation velocities, close to co-rotating. These clouds also tend to have high [N II]/Hα ratios, and are probably recycled disk gas. There is a tail of Hα-faint clouds at high negative V_{dev}, and nominal tens of kpc distances. These clouds have too much kinetic energy to have originated in the disk, and must be infalling material, perhaps stripped from dwarf galaxies. At these distances the infalling clouds are tidally unstable.

In summary, HVC optical emission fluxes suggest that the HVCs are not at $\sim 0.5-1$ Mpc, and there are likely two populations: disk and infall. The fraction of Lyman continuum photons escaping from the Milky Way disk is small, ~ 0.02. Several lines of evidence indicate that a second source beyond photoionization is operating in the Magellanic Stream and possibly HVCs, and we need better interpretations of this source and its role in Hα production.

References

Bland-Hawthorn, J., Veilleux, S., Cecil, G.N., Putman, M.E., Gibson, B.K. & Maloney, P.R. 1998, MNRAS, 299, 611

Bland-Hawthorn, J. & Maloney, P.R. 1999, ApJ, 510, L33

Blitz, L., Spergel, D.N., Teuben, P.J., Hartmann, D. & Burton, W. B. 1999, ApJ, 514, 818

Bregman, J.N. 1980, ApJ, 236, 577

Charlton, J.C., Churchill, C.W., & Rigby, J.R. 2000, ApJ, 544, 702

Danly, L., Albert, C.E. and Kuntz, K.D. 1993, ApJ, 416, L29

Einasto, J. & Lynden-Bell, D. 1982, MNRAS, 199, 67

Giovanelli, R. 1981, AJ, 86, 1468

Haffner, L.M., Reynolds, R.J., & Tufte, S.L. 2001, ApJ, 556, L33

Klypin, A., Kravtsov, A.V., Valenzuela, O., & Prada, F. 1999, ApJ, 522,82

Rand, R.J. 1998, ApJ, 501, 137

Reynolds, R.J., Haffner, L.M., & Tufte, S.L. 1999, ApJ, 525, L21

Sembach, K.R. et al. 2000, ApJ, 538, L31

Tufte, S.L., Reynolds, R.J. & Haffner, L.M. 1998, ApJ, 504, 773

Tufte, S.L. 2001, BAAS to appear

van Woerden, H., Schwarz, U.J., Peletier, R.F., Wakker, B.P. & Kalberla, P.M.W. 1999, Nature, 400, 138

Wakker, B.P. & van Woerden, H. 1991, A&A, 250, 509

Wakker, B.P. & van Woerden, H. 1997, ARA&A, 35, 217

Weiner, B.J., & Williams, T.B. 1996, AJ, 111, 1156

Weiner, B.J., Vogel, S.N. & Williams, T.B. 2000, astro-ph/0008263, to appear in Gas and Galaxy Evolution, ed. J. Hibbard, M. Rupen, & J. van Gorkom

Zwaan, M.A. 2001, MNRAS, 325, 1142